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NASA TECHNICAL TRANSLATION NASA TT ~~F-15~~ 211

THE EARTH'S HYDROMAGNETIC DYNAMO

S. I. Braginsky

(NASA-TT-F-15211) THE EARTH'S HYDROMAGNETIC DYNAMO (Linguistic Systems, Inc., Cambridge, Mass.) ~~29~~ 36 p HC $3.50 CSCL 08N

N74-14089

Unclas

G3/13 26048

Translation of: "Gidromagnitnoye Dinamo Zemli," Priroda, No. 9, Sept. 1973, pp. 32-41.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D.C. 20546 JANUARY 1974

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F-15, 211		

4. Title and Subtitle	5. Report Date
THE EARTH'S HYDROMAGNETIC DYNAMO	January 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
S. I. Braginsky	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
LINGUISTIC SYSTEMS, INC. 116 AUSTIN STREET CAMBRIDGE, MASSACHUSETTS 02139	NASW-2482
	13. Type of Report & Period Covered
	TRANSLATION
12. Sponsoring Agency Name and Address	
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of: "Gidromagnitnoye Dinamo Zemli," Priroda, No. 9, Sept. 1973, pp. 32-41.

16. Abstract

It has long been known that the earth has a magnetic field. It was at first supposed that the North Pole was the origin of the field. It is now known, however, that the earth is itself a magnet and so the source of its own magnetic field.

The article discusses the origin and various characteristics of the geomagnetic field that have been discovered as a by-product of paleomagnetology. Different theories accounting for it, for example, the hydromagnetic dynamo theory, illustrated in the article by small-scale phenomena, are presented. The epochal variations of the geomagnetic field are presented.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	UNCLASSIFIED - UNLIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	~~28~~ 30	3.50

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THE EARTH'S HYDROMAGNETIC DYNAMO /32*

S. I. Braginsky†

The Earth is a Large Magnet

It has long been known that the earth has a magnetic field. Anyone who owns a compass can be easily convinced of this fact. The magnetic needle's remarkable ability to indicate north is widely used in practice, especially by sailors. But they could only guess as to why the needle acted this way.

For example, many people thought that the North Star attracted the needle. This seemed very plausible until 1492, when Columbus on his famous voyage observed that in the middle of the Atlantic Ocean the needle deviated from the geographical meridian by 12° to the west. This was how the magnetic deviation was first discovered. Just a few decades later, it was demonstrated that a magnetic needle freely suspended at the center of gravity is poised, not horizontally, but at a particular angle of inclination to the horizon. This angle varies for different parts of the earth's surface.

The distribution of the angles of inclination around the world appeared very similar to the distribution of the magnetic force lines at the surface of a spherical magnet. One such magnet was specially prepared by W. Gilbert (1544-1603), a physician in the court of the English queen, Elizabeth I. He called it "terrella," meaning "little earth." The resemblance that he noted helped us formulate for the first time the fundamental hypothesis on the origin of the geomagnetic field: the earth itself is a magnet, and so the source of the magnetic field that we observe is our own planet.

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*Numbers in right-hand margin indicate pagination in foreign text.

†Doctor of Physical and Mathematical Sciences (see pg. 28).

In a first, very rough approximation (ignoring the deviation): A magnetic field can be formed by the field of a dipole located in the earth's center and running from the northern geographical pole to the southern.

Since the time Gilbert first suggested in 1600 that the earth was a large magnet, we have accomplished a great deal in further defining the properties of this magnet and its field. Numerous observations have determined the field's magnitude and direction at many points on the earth and for many moments in time. On the basis of these findings and with the help of a method presented by F. Gauss for a mathematical description of the field, we learned that its primary sources were actually located inside the earth, but the question concerning the physical nature of these sources remained mysterious for a long time. This is really not surprising because the innermost recesses of the earth are inaccessible for direct observations. Therefore we can only determine the sources situated there by indirect indications.

Not too long ago, at a discussion on the nature of the geomagnetic field, a great number of totally different hypotheses were enumerated. The most radical of these is presented by P. M. S. Blekett who postulates, especially for this circumstance, a new fundamental law of nature according to which any rotating body has a magnetic moment that is proportional to its moment of momentum. According to other theories, ferromagnetic substances at the earth's crust or core may be the field's primary origin. It was assumed that a huge pressure in the earth's core ($3 \cdot 10^6$ atm) raises the Curie point[1] to such /33

[1]At a temperature below the Curie point, such substances as iron, nickel, etc. ("ferromagnetic substances"), are capable of spontaneous magnetization. Each ferromagnetic substance has its own distinctive Curie point value.

an extent that a hard internal core[2] becomes ferromagnetic. We have also tried to explain the currents at the earth's core by the existence of a thermoelectromotive force at the boundary of the core--in the mantle. Other theories have also been suggested.

Today we can eliminate so great an uncertainty. This is due to a considerable extent to the progress in paleomagnetology, a young science that studies the magnetic field of past geological epochs according to the residual magnetization of the rock.[3] In examining this "petrified" magnetism, we learn that the earth's magnetic field repeatedly experienced a change in polarity during past geological epochs, while maintaining its own primarily dipolic nature. These "re-polarizations" occurred during a period of about ten thousand years. Thus, according to geological time scales, this process happened very fast. So we must reject the hypotheses that relate the geomagnetic field directly to the earth's rotation. We must also reject the assumption that a constant magnetization is the field's primary source. Ferromagnetic sources can play only a secondary role in the magnetic field of the entire planet. Yet, these sources are strongly evidenced in local anomalies, such as, for example, the famous Kurskaya

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[2]According to contemporary ideas, the earth's formation can be described (very schematically) in the following manner: A hard outer cloak, also called a mantle, has a radius $R = 6.37 \cdot 10^3$ km. The earth's liquid core has a radius $R = 3.47 \cdot 10^3$ km, and within that core there is a hard, so-called internal core with a radius of about $0.4R^1$.

[3]Many species of rock contain ferromagnetic elements. When igneous rock cools and its temperature falls below that of the Curie point, these elements become magnetized in the earth's field. In addition, at the formation of sedimentary rocks, light ferromagnetic particles magnetized in the earth's field are distributed throughout the field. So, a geomagnetic field is imprinted in various rocks at the instant of their formation. Using very precise, special methods of paleomagnetology, we can establish the direction and intensity of this field.

magnetic anomaly. It's also difficult to relate the hypothesis of the field's thermoelectric origin to the field's rapid reformations, since the thermal climate within the earth can only change very slowly.

The beginning of the contemporary views on the nature of the geomagnetic field was marked by the theory proposed by J. Larmor as early as 1919. This theory is linked to the similar question on the origin of magnetic fields in sunspots. Larmor postulated that when there is motion of a solid mass of matter that has good electric conductivity, a magnetic field can result from the process of electromagnetic induction, just as the electric current and the magnetic field of a self-generating dynamo are created. This device subsequently received the name "hydromagnetic dynamo." The earth's liquid core apparently has a metallic conductivity; hence the earth's hydromagnetic dynamo can operate here. The development of this hypothesis, after more than a 25-year stagnant period, was resumed by the work of the Soviet physicist, Ya. I. Frenkel' and the American physicist, W. El'zasser, who have theorized that thermal convection in the liquid core can set the earth's dynamo in motion and create a geomagnetic field.

Direct observation of the geomagnetic field, and also the determination of its past intensities (by paleomagnetic and archeomagnetic[4] methods) are revealing ancient variations with periods of about $\sim 10^2 - 10^3$ yrs. With the passing of time the picture of these variations changes in a complex manner. On the average it shifts to the west at the rate of about 0.2° per year--the field's so-called western drift. This indicates that the origin

[4]Archeomagnetic methods are similar to paleomagnetic, but in place of rock, they use air bricks, ceramics, and other man-made objects.

of the geomagnetic field is something very mobile that can alter in extraordinarily short times by geological standards. The theory of the earth's hydromagnetic dynamo is entirely in keeping with such a situation.

So we see that the earth is a large electromagnet and the fundamental question of geomagnetism consists in determining, according to magnetic field data received at the earth's surface, how an electric power station deep within the earth, which feeds this electromagnet, is set up.

What is a Hydromagnetic Dynamo

Self-energizing dynamos are widely used in industry. As is well known, when there is motion of a conductor in a magnetic feld, an electromotive force of induction is generated. This e.m.f. is perpendicular to the force lines and to the direction of the motion. In self-generating dynamos a magnetic field necessary for the stimulation of an electromotive force is maintained because part of the polarizing current in the conductor is directed into the coils of the electromagnet that creates this field.

We could attempt to construct a similar model of the self-sustaining mechanism of the earth's magnetic field. However, the hydromagnetic dynamo that we are interested in differs considerably from common self-energizing generators. For we do not use in it the insulated wires, sliding contacts, and other devices that allow the electric current to be directed along the paths intended by the designer. A hydromagnetic dynamo represents a solid mass of moving conductive fluid where the currents can flow, generally speaking, "however they please." So the first step in the theory of the hydromagnetic dynamo lies in demonstrating the principal ability of the magnetic field to self-energize /34 when there is movement of homogeneous conductive fluid in a globular region; and this is certainly not a simple task. Yet, T. Kauling accomplished this. Already in 1934 he demonstrated a remarkable theorem to the effect that a stationary hydromagnetic dynamo, in which the fluid movement and the magnetic field have a symmetry relative to some axis, is impossible. It follows, then, that a double-gauged dynamo is virtually impossible. Therefore, in studying the hydromagnetic dynamo, we must deal essentially with a three-faceted problem. This indeed complicates the mathematical side of the problem and also makes a graphic presentation of the earth dynamo mechanism very difficult.

The hydromagnetic dynamo theory involves a unique problem among the physical theories, and that is: does a solution to the corresponding mathematical problem actually exist? This is an extremely important question which should by no means be considered lightly. Attempts at a solution by direct numerical calculation, not entering into the physics of the matter deeply enough, were not completely successful. The first model of the earth's dynamo, in which there was some motion not symmetrically related to the earth's axis, was constructed mathematically by E. Bullard[5] and Kh. Gellman in 1954. This model played an important role in the development of the earth dynamo theory and many essential features proved to be correct. Yet it was later discovered that this model in reality could not "work," so what was accepted as an approximate solution represents only the first members of a series that branches off.

Before discussing the earth's dynamo it would be useful, if /34 only in rough examples, to imagine how the self-generation of the current and the magnetic field can take place. We can clarify this very simply in the example of the so-called unipolar disc dynamo, studied by Bullard in 1955 (Fig. 1). Let the conducting

[5] E. G. Bullard. The Origin of the Magnetic Field, "Priroda," 1960, No. 12.

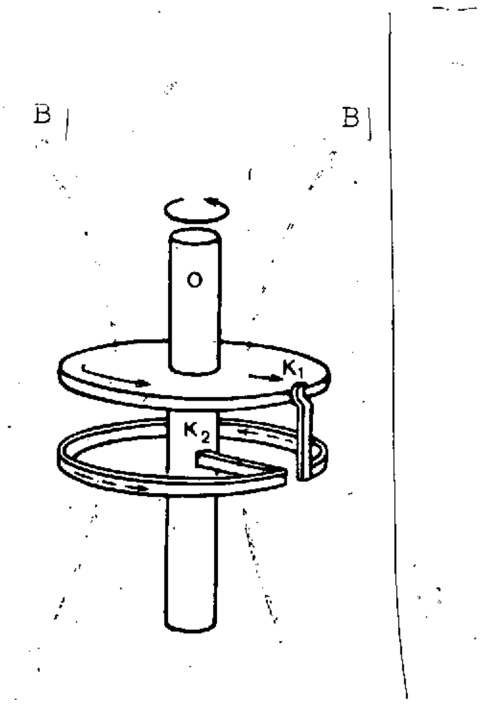

Fig. 1. A self-generating disc dynamo. A conducting disc rotates together with conducting axis O, as shown by the arrows. We can assume that some priming magnetic field running upwards initially existed. When the disc rotates, an electromotive force, directed towards the periphery of the disc, arises (i.e., along its radius). On account of this, a current will flow across sliding contacts K_1 and K through the ring (as shown by the arrow). This current creates magnetic field $\vec{B}$, which in turn, increases the e.m.f. of the current. With a great enough rotation rate, and a sufficiently low circuit resistance, the process can be multiplied.

disc rotate in the magnetic field $\vec{B}$ parallel to its axis. When there is motion with the rate of $\vec{v}$ in the magnetic field $\vec{B}$, an electromotive force is induced. This force is proportional to vB and directed perpendicularly to both the rate and the field, i.e., in the given situation, along the disc radius. The electromotive force of induction creates a current in the coil (or coils), and this current, in its own turn, maintains the magnetic field $\vec{B}$ that is necessary for induction. It's evident that the current and the field will be self-sustaining, if the rate of disc rotation is great enough, and the electric resistance of the disc and loop are small enough.

We will show now in a simple example how to do without insulating coils and how to achieve self-generation in a solid conductor. Let's examine first the large conductor located in the outer magnetic field $\vec{B}_0$, in which a rotating cylinder with an axis parallel to $\vec{B}_0$ is insulated. Let there be an ideal

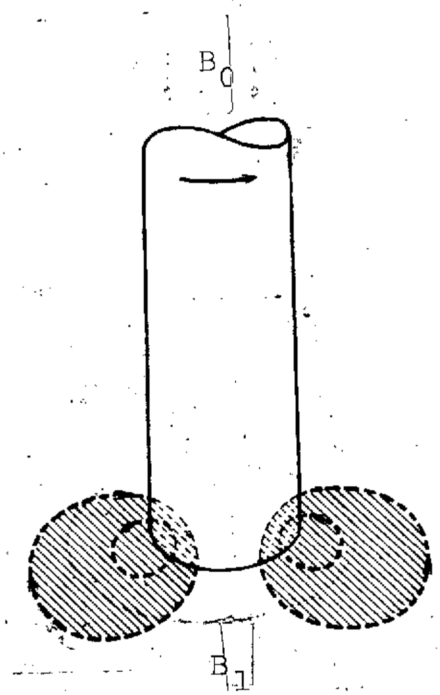

Fig. 2. A self-generation of a magnetic field in a solid medium by a rotating cylinder. A conducting cylinder is placed in a solid conducting medium (as shown in Figure 2). We make electrical contact on the cylinder's surface. The cylinder rotates as is shown by the arrow near the upper cut-off. Primary field $\vec{B}_0$ is parallel to the cylinder's axis. In these circumstances, closed currents are introduced in the planes that pass through the cylinder's axis (e.g., in the plane of the sketch). These currents create a secondary field $\vec{B}_1$, whose force lines envelope the rotating cylinder in a ring.

electrical contact between the cylinder and the remaining part of the conductor. Then because of the e.m.f. of induction, in the meridianal planes that pass through the cylinder's axis, a current arises, as shown by the dotted lines. This current creates a secondary magnetic field $\vec{B}_1$, whose force lines have the shape of rings perpendicular to the initial field $\vec{B}_0$. If we can now arrange two such cylinders, reciprocally perpendicular, as shown in Fig. 3, then the secondary field of each of the cylinders will play the role of the primary (inducing) field for the other cylinder. When the rotation rate is great enough and the electric conductivity of the substance is great enough, then a self-generation of the field will take place. This was

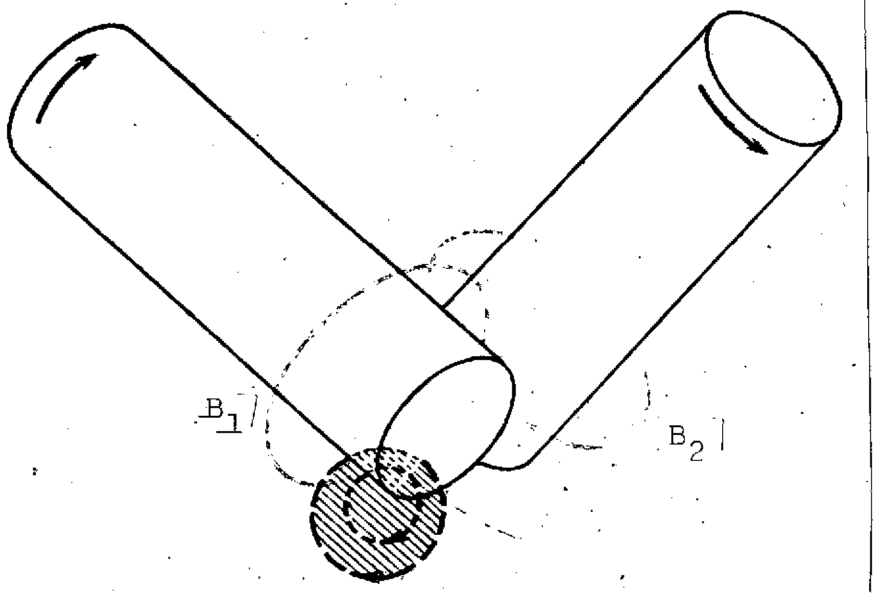

Fig. 3. A self-generating dynamo (according to F. Lous and I. Wilkins). In a continuous conductive medium, two rotating cylinders are set up facing each other at right angles (as in Fig. 2). The secondary field of each of these ($\vec{B}_1$ and $\vec{B}_2$) serves as a primary field for the other. This illustration shows that in a continuous conductive medium, such movements of its parts can take place when a magnetic field is created.

demonstrated experimentally by F. Lous and I. Wilkinson who set up such a system. Earlier, in 1958, A. Gertsenberg theoretically demonstrated the self-generation ability of a similar system, in which rotating spheres were studied in place of cylinders. This was one of the first demonstrations of the principal capability of a hydromagnetic dynamo.

The Magnetic Field in a Moving Conductive Medium

Although the example cited demonstrates the principal ability of the hydromagnetic dynamo, the paths chosen especially for it are far from those we can expect at the earth's core. To examine a dynamo of a more common (and more natural) nature, we can conveniently use a remarkable characteristic of the magnetic force lines. Kh. Al'ven[6] first determined this property at the outset of magnetic hydrodynamic theory.

Al'ven illustrated that in an ideally conducting fluid, the magnetic force lines are in a sense fastened to the substance, and with the movement of the substance the lines move together with it. Figuratively speaking, when there is ideal electric conductivity (as $\sigma = \infty$) the magnetic field is "frozen" in the substance. This is easy to understand when we recall that according to Faraday's law of induction, the e.m.f. along any closed circuit connected to the substance is proportional to the change in the magnetic flux passing through this circuit. So that large currents do not incessantly arise in a substance where $\sigma = \infty$ the e.m.f. along any such circuit must be equivalent to zero, i.e., the magnetic flux through any circuit must not change. What this means is that the force lines move together with the substance.

[6] Kh. Al'ven, Cosmic Electrodynamics. Moscow, Foreign Language Publishing House, 1952; Kh. Al'ven, K.G. Fel'tkhammer, Cosmic Electrodynamics, 2nd edit, Moscow, "Mir" Press 1967. [It is now acceptable to write Kh. Al'ven--Editor's Note.]

In a real conducting medium, of course, $\sigma \neq 0$. Thus, with the motion of the substance there is only a greater or a lesser tendency for the animation of the force lines, but there is not a complete animation. In other words, when there is a finite conductivity, the force lines are not only carried away by the substance, but they also are able to "infiltrate" it. This reverse infiltration partially hinders the animation of the force lines by the substance.

Because of the animation of the force lines and also axial symmetry, a significant effect on the strengthening of the field is already possible. This effect is linked to the influence of the non-uniform rotation of the fluid in the core on the magnetic field.

The movement of the earth's core is determined, to a remarkable extent, by its rotation around the axis, more precisely, by the Coriolis forces that result in these circumstances. As is well known, these forces are perpendicular to the rate of the matter. Thus, they deflect the radial currents in the azimuthal direction--to the west and to the east. In the earth's core a balance between the Coriolis and other[7] forces is achieved with azimuth speeds great enough, and a state of adequately fast non-uniform rotation is established in the core. You can imagine, for example, that the outer parts of the core move primarily to the west, and the inner parts to the east. The indirect evidence of non-uniform rotation is, namely, the magnetic field's observed western drift with a rate of ~0.2° per year, which gives us a measure of the non-uniform rotation.

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[7]The Archimedean force is most likely the basis of these forces. It results from non-uniformities of the structure and temperatures in the core. On masses less dense (e.g., the hotter ones) it acts upwards along the radius, and on the denser masses--downwards.

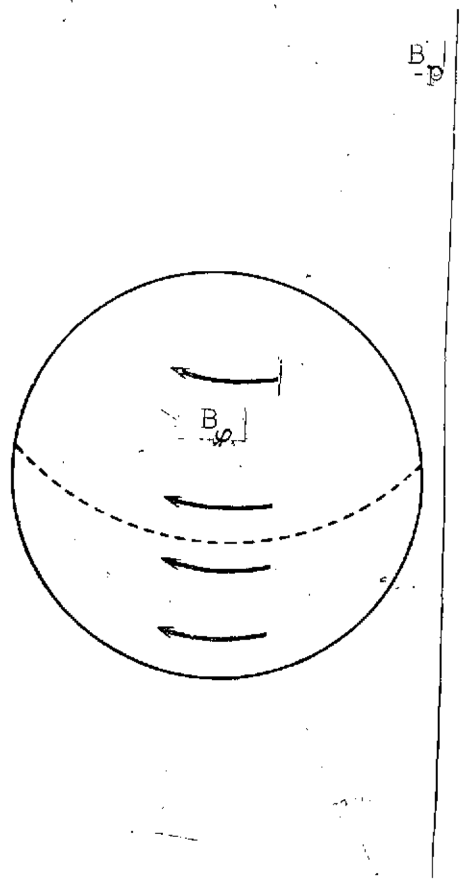

Fig. 4. The formation of the toroidal field B_1 from the meridional field B_1 in the earth's liquid core. The matter in an electrically conductive fluid core moving east to west in the external regions and west to east in the deeper regions, attracts a magnetic field that is "frozen" into it. (The picture shown is in a coordinate system, relative to the earth's stationary mantle.)

A field of the axial dipole type observed at the earth's surface evidently penetrates to the core. We shall call it the meridional field and designate it by $\vec{B}_p$ (Fig. 4). What precisely is the influence of the non-uniform rotation on this

field? Uniform rotation of a core, as of a hard body, would simply turn the field without really changing it. If, however, /36
the outer layers of the core rotate in a westerly direction, and the inner layers in an easterly direction, then the force lines of the field $\vec{B}_p$, while being carried off by the substance, are stretched in a longitudinal direction, creating the so-called toroidal field $\vec{B}_\varphi$ (Fig. 4). In non-uniform rotation, particles of matter move with a different angular rate. Therefore, in time one particle after another completes an infinite number of turns. If the force lines were totally carried away by the substance ($\sigma = \infty$) then a limitless "winding" of the currents of field B_φ would take place and its magnitude would increase infinitely. In fact, because of the finite conductivity, the reverse infiltration of the force lines limits the growth of field B_φ and some finite value is established. We will see that a related role of the processes of animation and infiltration of the lines is determined by a dimensionless parameter R_m, customarily called Reynold's magnetic number. This parameter is proportional to the conductivity of the fluid, the typical rate of non-uniform rotation v and to the characteristic size L of the region where the motion takes place. It is expressed by the following formula:

$$R_m = \frac{4\pi\sigma v L}{c^2}.$$

So, due to the balancing of the elongation and attenuation processes, the toroidal field $B_\varphi \sim B_p R_m$ is established.

If we accept, as the conductivity of the core, the order as that of molten iron, and if we take as the characteristic size and rate, the core's radius and the rate that corresponds to the observed drift, then we will get $R_m \approx 10^2 \div 10^3$. Thus the mechanism of non-uniform rotation can create a toroidal field of several hundred gauss, while the field on the earth's surface is $\vec{B}_p \sim 0.5$ gauss. We do not observe the toroidal field as it is limited by the size of the core, just as the field of a closed solenoid is limited by its currents. The force lines of the toroidal field are closed and do not emanate from the core. It is this field, however, that turns out to be the fundamental field in the earth's core. The formation of the field B_{φ} plays a very important role in the mechanism of the earth's dynamo. We represent this part of the dynamo mechanism conventionally in the form

$$B_p \xrightarrow{\zeta} B_{\varphi},$$

where ζ indicates the non-uniform rotation.[8] To form a closed cycle of self-generation, we need yet another mechanism of the type $B_{\varphi} \rightarrow B_p$, i.e., the mechanism of the generation of the meridional field from the toroidal.

Two Types of Hydromagnetic Dynamos

The movements symmetrically related to the axis (i.e., axially symmetrical) evidently shift only the lines of the field B_{φ}, but they cannot create the field $\vec{B}_p$ from it and consequently, do not produce the dynamo's mechanism, as follows from Kauling's theorem. For the process of $B_{\varphi} \rightarrow B_p$, we need more complicated generating motions, ones that do not have axial symmetry. We shall designate these by $\vec{v}'$.

At the present time, two types of generating motions $\vec{v}'$ are being studied. Two types of hydromagnetic dynamos correspond to them. We assume there is a small-scale turbulence in a dynamo of the first type. Turbulent vortexes, similar to cyclones and anticyclones observed in the earth's atmosphere, while interacting

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[8] This expression should read: Field B_p due to non-uniform rotation ζ creates field B_{φ}.

with the field B_φ, give rise to the field $\vec{B}_p$. This mechanism first suggested by E. Parker, can be depicted in the following manner. A spiral motion in the vortex, creates, in the lines of the field B_φ, a loop in the shape of the letter Ω and reverses this loop while rushing to set it up in the meridional plane (Fig. 5). The current corresponding to this loop has a component that is parallel to the field B_φ. The fusion of the currents of many small loops creates an average current j_φ, which in turn creates the field $\vec{B}_p$. In order for the effect of many loops to take place and not fade, a definite sign of a screw must be present.

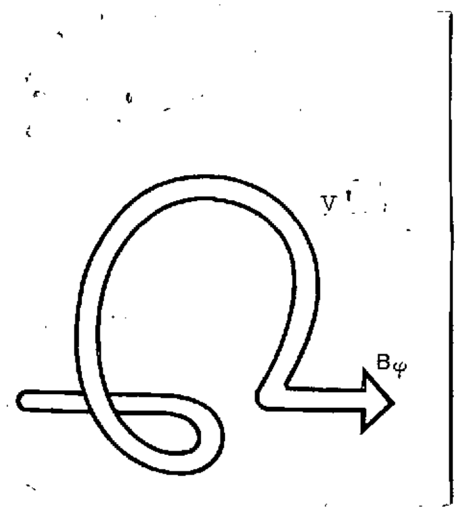

Fig. 5. The formation of the meridional field $\vec{B}_p$ from the toroidal field B_φ. On the left we see that a vortex similar to a cyclone (v') creates a loop in the lines of the field $\vec{B}_\varphi$ that has the shape of the Greek letter Ω and inserts this loop in the meridian plane. There is a large number of small loops of the type Ω in the plane, through which currents j_φ flow. By their own mutual activity these currents create the earth's magnetic field $\vec{B}_p$ which is a hundred times smaller than the internal toroidal field B_φ.

in the spiral motions (for example, the majority of vortexes have a right spiraling motion). A detailed inspection shows that in any correlation of fields B_φ and B_p, the interaction with the magnetic field of many randomly-distributed small-scale spiral vortexes with a definite indication of a screw, creates a mean current, parallel to the magnetic field. M. Shteenbek and his colleagues studied this effect in detail.[9] They called it the α-effect and showed that, without non-uniform rotation, self-generation of the field can take place at the expense of only one α-effect. In the earth's core, however, the action of the large scale non-uniform rotation is far more effective for the process $B_p \to B_\varphi$ than the α-effect.

Another type of motions $\vec{v}'$ which can close the generation cycle in a fluid with a very high electric conductivity was studied for the first time by the author. This type is the ordered large-scale motions, in which the rates $\vec{v}'$ are far smaller than the rate of non-uniform rotation v_φ, so that the entire motion as a whole differs very little from the axially symmetrical motion. The mechanism for generating the meridional field from the toroidal $B_\varphi \to B_p$ in this circumstance is very weak. However, owing to a high electric conductivity (large R_m), of an already weak deviation from axial symmetry, the field's attenuation can be compensated for at a loss in heat, and a self-sustaining dynamo can be created. In such an almost-axial symmetrical dynamo, the movement of fluid must be in spirals (very gently sloping spirals). And the method for creating the field $\vec{B}_p$ from B_φ is similar to the mechanism of the α-effect. Yet, it differs by the extreme orderliness of its motions and fields.

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[9] M. Shteenbek. Why the earth has a magnetic field, "Priroda," 1970, No. 7.

The "two-stepped" scheme for self-generation that is described is identical for both types of dynamos:

$$\begin{tikzcd} B_p \arrow[r, bend left, "\zeta"] & B_\varphi \arrow[l, bend left, "v'"] \end{tikzcd}$$

However these two dynamo types greatly differ in movements v' and in the changing fields B' connected with them. In order to clarify what exactly is the true nature of the motion and the true mechanism for generation, we must examine in detail the changes in the magnetic field in time and space.

<u>This Wide, Wide Spectrum...</u>

Systematic observations of the geomagnetic field at various points of the earth have been made for more than a hundred years. Many observatories, special ships, planes, and artificial satellites are now performing these observations. The causes of the changes in the field, i.e., its changes through time, are manifold. Hence, their characteristic lifetimes are very different--from one second up to many millions of years. There are two groups that sharply differ in variations. The first group is conditioned by external causes: processes in the earth's ionosphere and magnetosphere, the sun, and interplanetary space. These processes are responsible for the short-period section of the variation spectrum. They are the subject of one of the branches of geomagnetism; this branch studies the so-called "variable" field, which would probably be more aptly called "field of external origin." We won't go into the interesting phenomena associated with the variable field because they do not have a direct relationship to the earth's dynamo. However, they are used, for example, in the study of the electrical properties of the earth. /38

Another branch of geomagnetism is the research into the so-called "constant field," whose sources lie deep within the earth. It would probably be better to call it simply an internal field. A "constant" field also changes very complexly with time. These changes are called epochal variations; their periods are far greater than those of the variable field. Moreover, the earth's mantle holds some electrical conductivity. Therefore, processes within the earth's core with periods of less than several years are shielded by the mantle and are not detected on the earth's surface.

To represent the geomagnetic field and its changes we customarily use maps on which are lines of equal value of one element or another of the field. A schematic map of the variations in the vertical field component is shown in Figure 6.

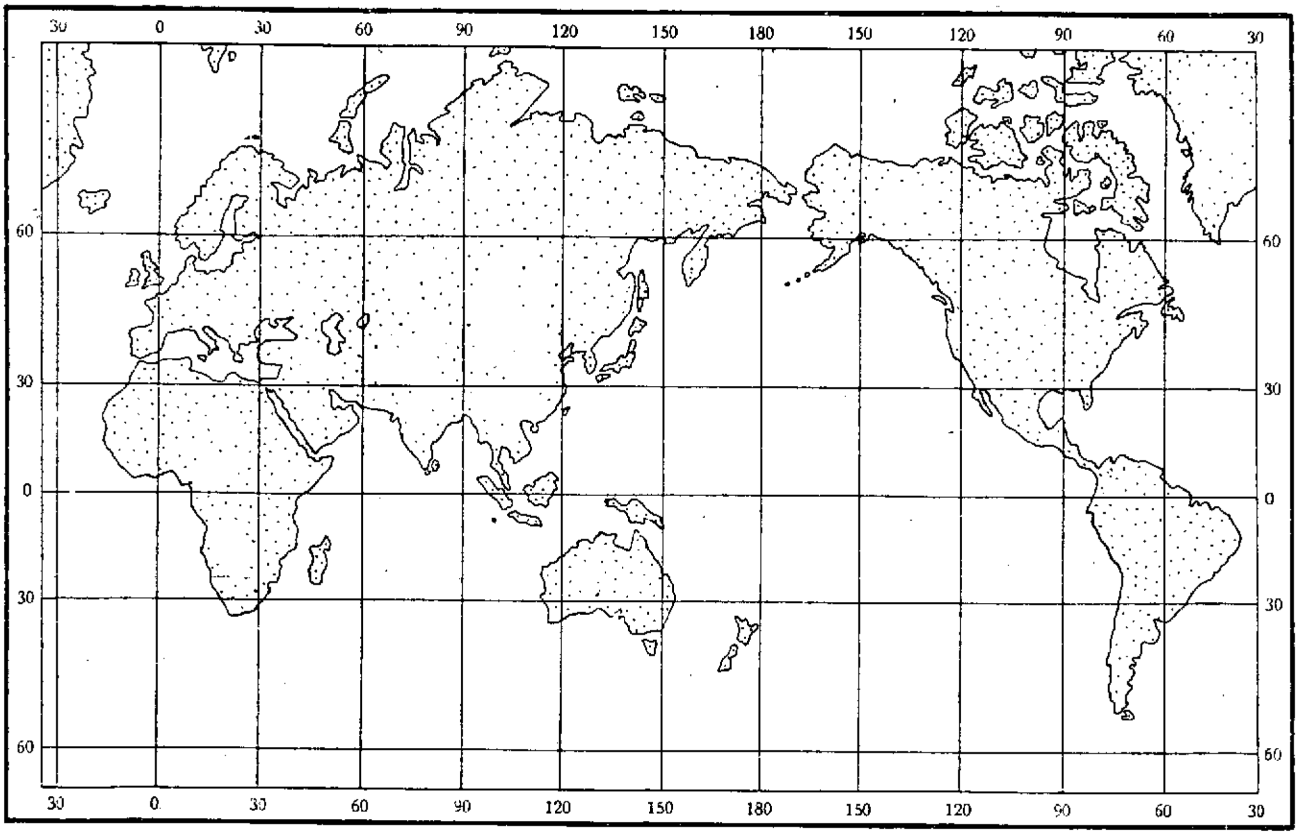

Fig. 6. The epochal variations in the magnetic field's vertical component in the period 1950-1955. The figures in the isolines are in units of 10^{-5} gauss/yr. Their positive value shows that in this period the vertical component increased and the negative decreased. The geographical coordinates are placed along the axis.

The map pertains to the time interval 1950-1955. In the course of time the picture changes intricately. It reveals, on the average, some displacement towards the west--the western drift. To explain the epochal variations in detail, we must know the changes in the field over a long period of time, far greater than the time span of the direct observation of the field. Archeomagnetic and paleomagnetic research shows that the fundamental part of the epochal variations in the field's direction occurs in changes with periods of about 10^3 years. This corresponds remarkably to the time of the core's discharge by the magnetic field with the velocity of the western drift. So the intensity of the field of the magnetic dipole fluctuates around some average value (close to the present value) where the minimum value of the dipole's field is roughly twice as small as the maximum. At the present, one period of this process, representing $8 \cdot 10^8$ years (Fig. 7) is traced. Moreover, a dipole sometimes changes its sign. The intervals of time between these "re-polarizations" are random, with an average value of $2 \cdot 10^5$ yrs for the last geological epoch. Sometimes, however, (for example, around $2 \cdot 10^5$ years ago) in the Permian epoch, re-polarizations were extraordinarily rare: once in every $\sim 10^7$ years. And finally, one more type of long-lasting variation is the slow shift in the position of the magnetic poles on the earth's surface. The paths of the magnetic poles, according to paleomagnetic research on types of different subsoils, vary remarkably. But, on the whole, about $5 \cdot 10^8$ years ago, the magnetic poles were situated in the /39 region of the present equator. These polar movements are naturally linked to the famous hypotheses on the drift of the continents. Variations with periods and the order of 10^2-10^3 years are the most fascinating of all for examining the dynamo mechanism. The part of the spectrum corresponding to these is shown in Figure 9.

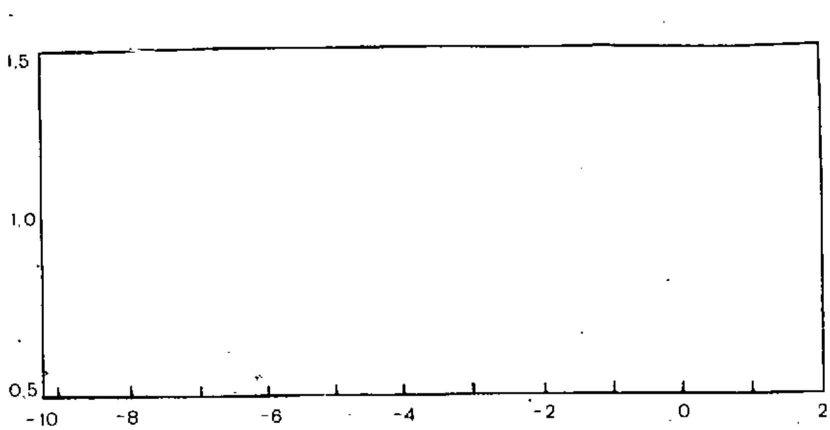

Fig. 7. The intensity of the earth's magnetic moment, according to archeo-magnetic data, averaged out according to 500-year time intervals (red dots and small circles: the small circles are the result of averaging less than three values, i.e., insufficiently accurate data). Along the abscissa we place time in thousands of years. Along the ordinate axis we place the magnetic moment in similar units. (The present-day value for a unit is customarily $8 \cdot 25^3$ gauss cm^3.) Using many pieces of data, we can draw a continuous line from the start of our era up to the present.

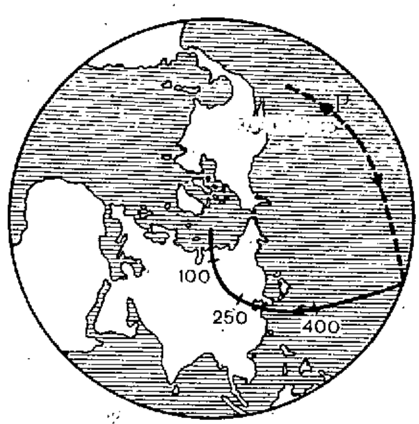

Fig. 8. Curves of the movement of the North Pole, based on European (red lines) and North American (black lines) data. The parts of the curve that pass through the southern hemisphere are plotted by a dotted line. (P - during the pre-Cambrian era.)

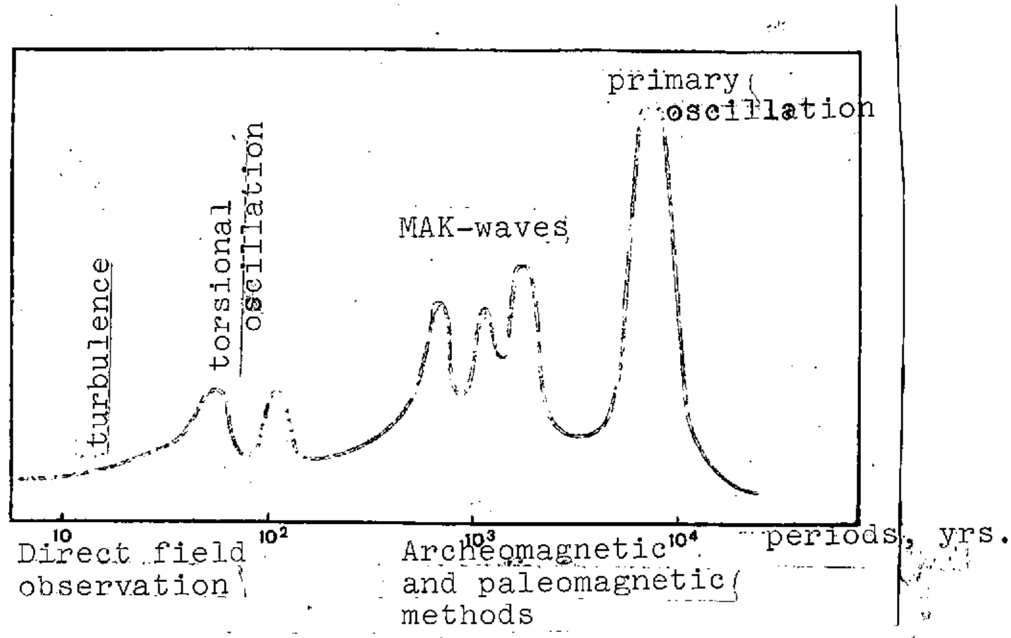

Fig. 9. A spectrum of the geomagnetic variations and the methods for determining them. Along the abscissa is the length of the variation's period in years.

The Magnetic Waves in the Earth's Core

Where, then, do the large-scale asymmetrical movements $\vec{v}'$ originate? The reason for the asymmetry of the movements in the core may be the instability of the symmetrical convection. The author has shown that there does indeed exist a mechanism of such an instability linked to the influence of those Archimedean forces that are formed by the basic convection. This mechanism must lead to the outbreak of large-scale (planetary-wide) movements having a contour of waves running in an azimuthal direction (along the change in the angle of longitude) with a rate comparable to that of the western drift. The inertia of the substance, in this case, is irrelevant because of the slowness of the motions. Mutually counterbalancing magnetic, Archimedean, and Coriolis forces play a substantial role in these waves. Therefore, the author named them "MAK-waves." It is precisely the development of the MAK-waves that creates the generating rates $\vec{v}'$. In this connection, corresponding components of the magnetic field B' also arise, having a form of travelling waves. Fields $\vec{B}'$ cause an angle (at the present time about 11°) between the earth's dipolic axis and the earth's rotational axis, non-dipolic components, and also the basic part of the epochal variations which are subsequently non-random external fluctuations, but a direct development of the dynamo mechanism. Thus the generation of the basic field and the generation of its epochal variations are closely linked with each other. From this standpoint, the western drift is a complex phenomenon. It is formed from the rotation of the core's mass relative to the mantle and also from the MAK-waves of various frequencies placed in it. The frequencies of the MAK-waves are determined by the intensity of the magnetic field in the core. It is remarkable that the observed periods of variation of about 10^3 years correspond to a field of several hundred gauss. This confirms the existence of such a large field B_ϕ in the core.

We note that small-scale turbulence would lead to a perfectly random variation picture. The high frequency part of the field's turbulent pulsations would generally not reach the surface because of a shielding in the mantle. But a low frequency part would have a type of "hum," i.e., separate random impulses.

The English scholar R. Hyde pointed to an important role of the slow magnetic waves in the mechanism of epochal variations. Moreover, he devised an interesting hypothesis that the boundary of the core with the mantle has irregularities in height by several kilometers. According to R. Hyde, a relief of this sort influences the motion in the core and as a result of this can be substantially manifested in epochal variations.

Apart from the slow epochal variations, variations with shorter periods--tens and hundreds of years--are also observed, the exact nature of which is unclear. Variations with 60-year periods relate to corresponding changes in the duration of a day, i.e., the rate of the earth's rotation. It's probable that they are connected with the magneto-hydrodynamic oscillations of a twisting type in the core, and also with some kind of disturbance at the core--the mantle border, the exact nature of which is still unknown.

We are still faced with an enormous experimental and theoretical task before we can successfully comprehend in detail all the types of epochal variations, and can elucidate both their nature, and, as a matter of fact, the nature of the earth dynamo.

The Motor Problem

Without a doubt, the theory of the dynamo shows the ability of a magnetic field to self-generate in a fluid conducive core, where you have a very common type of convection. Yet, it is important that the convection is adequately great and not too symmetrical. But, for a total explanation of the observed facts, we must also establish another theory besides the theory of the earth dynamo; that is, an adequately amplified "motor" theory, that sets it in motion. This requires the concurrence of several theories on the formation of the earth's core and on the possible sources of energy; in other words, theories on the sources of convection in the core.

At the present the facts on the core's composition, the quantity of heat discharged there, the viscosity of the liquid core, and the exact location and contour of its boundaries, are very incomplete. We hope, however, that with a detailed study of the hydromagnetic dynamo, we can define more precisely the properties of the earth's core.

The simplest cause of motions in the core is the discharge of radioactive heat. Heated matter has a low density. An Archimedean force that is directed upwards acts on it; whereas on the colder portions of the liquid this force will act directed downwards. But, such a simple explanation of convection in the core is confronted with difficulties. As it is known from thermodynamics, any heated motor has an efficiency less than that of the Karno cycle[10] equivalent to $(T_1-T_2)/T_1$ where T_1 and T_2 are the absolute temperatures at which the heat is input and output. In the core, the difference in the temperatures is not very great. Thus, the efficiency of the heated motor in the core cannot exceed a few percent. On the other hand, the engine power necessary for the dynamo's work (to compensate for the losses in heat discharge by the electric current) is great enough. This is tied to the existence of a large toroidal field in the core (a few hundred gauss). Moreover, the output of a large quantity of heat from the core also faces difficulty, since the thermal conductivity of the mantle is inadequate for this. The matter involving the output of such a quantity of heat by convection in the mantle is still unclear.

It's more likely that the motor of the earth's dynamo is of a non-thermal nature. Thus, its efficiency is not limited by the Carnot efficiency. Non-thermal convection at a lowering of the heavier and a rising of the lighter matter, can occur if there are some sources, lighter alloys arranged in the core's mass below, where the internal core is, or heavier ones from above, the boundary at the mantle. For example, it is possible that with

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[10]The Carnot Cycle is the cycle of an ideal thermal machine with the highest possible efficiency ratio.

the growth of a hard internal core due to crystallization of the liquid mass, some light alloys do not enter into the composition of the internal core, and while rising upwards, they create a convection in the liquid core.

The view has also been expressed that the stimulating action of the inertial forces, associated with the precession of the earth's axis, may be the source of convection.

The question on the causesof convection in the core still remains open.

The Dynamo and Geophysics

The theory of the self-generating hydromagnetic dynamo operating in the earth's core offers at the present the only acceptable explanation of the nature of the geomagnetic field. On the basis of this hypothesis we can develop an overall satisfactory picture of the earth's dynamo. But much of it is still arbitrary. So that the "dynamo hypothesis" becomes a workable "dynamo theory" we must reach the point where the number of parameters determined experimentally and collectively compared with the theory's predictions significantly exceeds the number of parameters (unavoidably) introduced speculatively and hastily /40
into the theory. It is essential that we develop the theory extensively and that we widen archeo- and paleo-magnetic research to attain detailed facts on the magnetic field over a long period of time. We must also link as closely as possible the dynamo theory with other branches of geophysics.

We can formulate from any geomagnetic field theory questions that require quantitative answers. For example, here are ten "why" questions:

1. Why is the geomagnetic field basicially a dipole directed along the earth's axis of rotation and equal to $\sim 8 \cdot 10^{25}$ gauss cm^3?

2. Why is there a smaller, yet quite substantial, transverse dipole (inclined to the magnetic axis) and also non-dipolic field components of a complex type?

3. Why do these deviations from the axial dipole undergo fluctuations with periods of about 10^3 yrs?

4. Why do short-period epochal fluctuations with periods of 10^2 yrs. or less occur? How are their form and spectrum defined?

5. Why do the western drift of the field and the epochal fluctuations take place? How do you correlate the drift's irregularities with the changes in the rate of the earth's rotation?

6. Why do the basic dipole and other field characteristics undergo oscillations with a period of $\sim 10^4$ yrs? How do you determine the period and shape of these oscillations?

7. Why did repeated changes in the sign of the basic dipole take place in the past? How do you explain the time intervals between the re-polarizations?

8. Why did the field's re-polarization take place for a period of $\sim 10^4$ years? How did this process exactly take its course?

9. Why did the magnetic intensity remain constant (except for short re-polarization periods) for great intervals of time of $\sim 10^8$-10^9 years? In other words how do you explain the relationship of the field to time with respect to the history of the earth's development?

10. Why, for a time on the earth's existence, were there large displacements of the magnetic poles along the surface?

The present dynamo theory satisfactorily answers all of these questions. Its answers, however, are basically qualificative. They often rest on supplementary suppositions.

The theory of the geomagnetic field must, of course, be in keeping with the data on the magnetic fields of other planets, especially planets of the earth's type. It is well known that Mars and Venus do not have their own fields analogous to that of the earth. In the case of Mars, this could be due to the fact that it is much smaller than the earth and, therefore, it has already expended the entire amount of energy necessary for the activization of convection. The absence of a magnetic field on Venus is probably due to its slow rate of rotation, for rotation plays an important stabilizing role and impedes the chaotization of large-scale motions within the core.

The development of the theory of the geomagnetic field must be closely tied to other questions about the formation of the earth's inner recesses. This will further define the theory of geomagnetism and will reduce the ambiguity in the views of the formation of the earth. Let's take a few examples. The intensity of the electrical conductivity of the earth's core offers just one parameter for determining the earth's make-up. By electric conductivity we can estimate its temperature. Geomagnetic research allows us to precisely ascertain these values of electric conductivity. If it is proven that a large flow of heat (which cannot be explained by thermal conductivity alone) moves outwardly from the core, then evidence of convection in the lower mantle would be produced. This question now creates a lot of controversy. It is a very important one for an accurate appraisal of the thermal history of the earth.

Changes in the past of the geomagnetic field's polarity are linked to sharp alternations of rates in the core. In this connection important questions arise about how they occur (to some extent randomly along with particular changes in the core or mantle--in general in the history of the earth). Finally, great shifts in the paleomagnetic poles are probably explained by a change in the position of the earth's rotational axis, and also by the drift of the continents, i.e., they are determined by the dynamics of the mantle. But it is namely the theory of geo-magnetism which must establish a feasible value for the deviation of the magnetic poles from the geographic poles. This value is essential for the paleo-magnetic method of determining the poles.

Further progress in the theory of the hydromagnetic dynamo will allow us to practically apply the results of geomagnetic research to a general system of geophysical data on the formation and history of the earth. This will help us to better understand both the nature of the geomagnetic field and the formation of the deepest regions within the earth.

Text under photograph:

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